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SEP 79 B ONKARAM, L A STROSCHEIN, R F GOLDMAN
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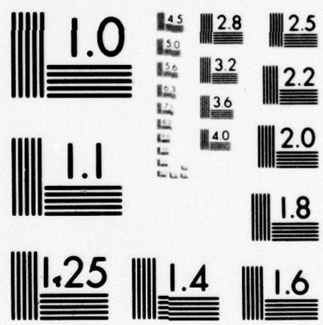

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Environmental heat stress, expressed as the ambient wet bulb globe temperature (WBGT), was measured using three different WBGT instruments: (a) the conventional shaded dry bulb, 15.2 cm black globe and naturally convected wet bulb thermometers, (b) a miniaturized thermometer kit, (c) a commercial WBGT instrument using thermistor sensors, and the WBGT was compared with (d) the ambient wet globe temperature (WGT) measured by a Botsball. Visual observations were made on the instruments at regular intervals and an auto-

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mated data collection system was also used to obtain data from thermocouples attached to the instruments. Statistically significant differences in WBGT readings were found among the instruments; however, the difference for a given environment was usually less than 0.5°C. Readings taken by visual observations resulted in WBGT values which differed by less than 0.3°C from those calculated from the automated data collection system. By using an equation derived for the Botsball, WBGT = 1.044 WGT - 0.187 in °C it is possible to convert the Botsball thermometer dial to indicate the conventional WBGT for outdoor environments; it then becomes a simple instrument for assessing environmental heat stress at the work site.

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Environmental heat stress, expressed as the ambient wet bulb globe temperature (WBGT), was measured using three different WBGT instruments: a) the conventional shaded dry bulb, 15.2 cm black globe and naturally convected wet bulb thermometers, b) a miniaturized thermometer kit, c) a commercial WBGT instrument using thermistor sensors, and the WBGT was compared with d) the ambient wet globe temperature (WGT) measured by a Botsball. Visual observations were made on the instruments at regular intervals and an automated data collection system was also used to obtain data from thermocouples attached to the instruments. Statistically significant differences in WBGT readings were found among the instruments; however, the difference for a given environment was usually less than 0.5°C. Readings taken by visual observations resulted in WBGT values which differed by less than 0.3°C from those calculated from the automated data collection system. By using an equation derived for the Botsball, $WBGT = 1.044\ WGT - 0.187$ in $^{\circ}$C it is possible to convert the Botsball thermometer dial to indicate the conventional WBGT for outdoor environments; it then becomes a simple instrument for assessing environmental heat stress at the work site.

Three Instruments For Assessment Of WBGT And A
Comparison With WGT (BOTSBALL)

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INTRODUCTION:

The wet bulb globe temperature (WBGT), one of the indices used for expressing the severity of an environment in terms of the heat stress imposed on man, has gained wide acceptance because of its apparent correlation with observed strain on the man.[11] Such an index has proved to be of value in eliminating adverse effects of heat at military training centers in the U.S. and it has also been shown that implementation of WBGT standards has reduced heat casualties in British troops.[8] The National Institute of Occupational Safety and Health has proposed the use of such an index to assess heat stress environments in industry.[7]

The WBGT index combines the four basic factors that influence the degree of heat stress, namely, air temperature, vapor pressure, air movement and heat radiation. These factors are assessed by using a dry bulb, wet bulb and globe thermometer. The dry bulb thermometer is an ordinary mercury thermometer which measures air temperature (naturally Ventilated). The wet bulb thermometer is also an ordinary mercury thermometer with a wick surrounding the bulb; it measures the effects of the evaporative cooling that occurs at unsaturated vapor pressure conditions at a particular air temperature. The conventional dry and wet bulb thermometer readings are obtained with an air movement of at least 4.57 m/sec induced by a sling to rotate a pair of dry and wet bulb thermometers ("sling psychrometer") or by a motor driven fan, pulling air across the thermometer bulbs ("aspirating psychrometer"). However, a naturally convected wet bulb thermometer, has been adopted for human heat stress assessment; it, like man, is not artificially ventilated, but is only affected by ambient air motion. The globe thermometer is a 15.2 cm, hollow, copper sphere fitted with an ordinary thermometer; it senses the air temperature, air movement and heat radiation.[5] The WBGT index for outdoor use is computed by using the formula: 0.7 natural wet bulb temperature + 0.2 globe temperature + 0.1 dry bulb temperature. The WBGT index for indoor use can be computed by using the formula: 0.7 natural wet bulb temperature + 0.3 globe temperature, although there are advantages to using the WD (Wet-Dry, or Oxford) index, 0.85 natural wet bulb temperature plus 0.15 dry bulb temperature when air and globe temperatures are equal.

Apart from the WBGT index, such indices as the effective temperature (ET), corrected effective temperature (CET) and heat stress index (HSI) have been used to assess heat stress.[12]

Today a variety of instruments are available which measure the WBGT index directly, and which also measure the three different temperatures from which the WBGT index can be computed. A fluid analogue computer based on the mercury-in-glass thermometer was developed to measure WBGT index directly.[9] A silicone diode circuit has also been described for direct measurement of the WBGT index.[4] In the present study we compared a conventional Standard WBGT kit (Fig. 1A) with two others; 1) the Weksler Instruments Corporation, under US Army contract, developed a small, portable wet bulb globe temperature kit which measures the dry bulb, wet bulb and globe temperatures and allows WBGT to be calculated by using a slide rule provided in the kit (Fig. 1B); this is referred to as WMK (Weksler miniaturized kit) in this report. For the black globe thermometer, this kit makes use of a hollow, copper cylinder, painted black which is just large enough to slide over the glass thermometer bulb, and is enclosed in a transparent, perforated plastic shield. 2) the Yellow Springs Instruments Co., Inc. also supplies a kit that can be used to measure the WBGT index, both indoors and outdoors; the WBGT index as well as the individual temperatures can be directly read on the meter provided. This instrument makes use of the standard 15.2 cm hollow globe and is referred to as the YHI (Yellow Springs Heat Stress Instrument) in the following description (Fig. 1D).

Botsford has developed a wet globe thermometer which consists of a dial thermometer with the heat sensor enclosed by a 6 cm black copper sphere completely covered with a black cloth; this instrument, now known as the "Botsball", measures the "wet globe temperature" (WGT) (Fig. 1C).[1] This is compared to WBGT in what follows.

Brief and Confer compared the wet globe temperature (WGT), effective temperature (ET), corrected effective temperature (CET) and heat stress index (HSI) with the WBGT.[2] They showed a good relationship between WGT and WBGT and suggested the following equation: WBGT = 1.044 WGT − 2.64 in °C (WGT = 0.958 WBGT − 3.2 in °F); the correlation was derived from 34 sets of data collected in a test chamber. Mutchler and Vecchio developed empirical relationships among heat stress indices derived from a series of studies of 14 hot industries[6] and developed equations for comparing the various indices with WBGT at various wind velocities; in the overall range they showed a good relation between WGT and WBGT, and suggested the relationship WBGT = 1.05 WGT + 1.14 in °C. Ciriello and Snook studied the relationship between WGT and WBGT under varied radiant, humidity, windspeed and dry bulb temperature conditions[3] and concluded that if radiation, humidity and air movement are available, WGT can precisely predict the WBGT within acceptable limits; the equation WBGT = 1.07 WGT + 0.80 in °C was given for all environments.

All these studies indicate a relationship of WGT with WBGT in indoor environments, where the relation WBGT = 0.7 natural wet bulb + 0.3 globe is used for computing WBGT.

The purpose of this present investigation is to compare both the US Army adopted Weksler kit and the YHI kit with the Standard kit, and simultaneously, to compare the ambient WGT described by Botsball with the WBGT obtained by using the Standard kit. The WBGT indices calculated with these devices, as well as their individual component readings (i.e. the dry bulb, the wet bulb and the globe temperatures) are to be compared with the respective temperatures from the Standard kit. It is also necessary to see whether these kits really conform to the Standard kit despite the fact that, although they have been built to simulate the Standard kit, they differ from it; the dry bulbs are shaded differently and placed differently in each kit, different sensors are used in the YHI kit, and a black globe analog is used in the WMK instead of the 15.2 cm globe.

METHODS:

The experimentation was carried out on the roof top of the United States Army Research Institute of Environmental Medicine (USARIEM) building where facilities were available to station the recording instruments used in the study. After a careful consideration of the various structures present on the roof of the building, a location was chosen where the instruments did not receive radiation from other structures, did not get shaded and did not get shielded from the wind.

Copper-constantan thermocouples were used to measure the temperatures from the instruments. As it was necessary to measure the globe, the wet bulb and the dry bulb temperatures from each WBGT kit, a three point, copper-constantan, Type T, thermocouple harness was used. Thermocouples were tied to the bulb of the thermometers of the Standard and Weksler kits, the thermocouples were attached to the sensors using a thin, two-sided, adhesive tape. In the case of the Botsball, the dial portion of the instrument was removed and the thermocouple introduced into the stem. The harnesses were connected to low thermal decade switches (decades) in a HP scanner.

A Cambridge Systems instrument, 110 automatic meteorological and dew point measuring system which measures ambient temperature and dew point was connected to the decades in the scanner. An Eppley pyranometer which measures radiation was also connected to the decades in the scanner. A three-cup anemometer which measures wind speed, was connected to a HP universal counter. A HP digital voltmeter was used to read the thermocouples in conjunction with a HP timing generator and a HP-IB digital clock. The HP scanner, HP universal counter, HP digital voltmeter, HP timing generator and HP-IB digital clock were connected by an IEEE Standard digital interface with a HP 9825A calculator.

The Standard kit was set up as follows. Retort stands with 1.8 meter long rods were used as supports to hold a horizontal rod 1.22 meter above the ground. The globe thermometer was constructed from a 15.2 cm globe and an ordinary mercury thermometer. The wet bulb thermometer was constructed from an ordinary thermometer with a wick, tied to the bulb, hanging in distilled water in a 50 ml conical flask filled up to the neck. The dry bulb thermometer was an ordinary thermometer that was shielded from the sun by aluminum plates. The globe thermometer, the dry bulb thermometer and the wet bulb thermometer were hung, separated by a distance of 61 cm from each other on the horizontal rod (Fig. 1A).

The WMK was set up to the right of the Standard kit and was held in position on a screw attached to the clamp of a retort stand. The wet bulb reservoir of the kit was filled up with distilled water. As it was a little difficult to pour water into the WMK wet bulb reservoir, a hypodermic syringe was used to inject distilled water. The WMK was arranged so that the perforated shield of the black globe thermometer was pointed toward the sun.

The YHI was set up to the right of the Weklser kit. The wet bulb reservoir of the YHI was filled with distilled water. As the tripod supplied with the kit did not provide adequate support, lead weights were attached to the legs so that the instrument would not be tipped over by wind.

The Botsball was hung on the horizontal rod of the Standard kit. The Botsball was periodically dunked in distilled water contained in a beaker.

The three cup anemometer was held in position on the horizontal rod of the Standard kit. The Eppley pyranometer was mounted on a stand by the side of the Standard kit. The Cambridge systems instrument was positioned on a heavy stand in front of the Eppley pyranometer.

At the onset of the study on each day, all instruments, including the Botsball, were left for about an hour to reach equilibrium conditions before readings were made. The wet bulb reservoirs of all the kits were checked from time to time for distilled water. The wicks of the wet bulbs were checked for cleanliness. The Botsball was dunked from time to time to keep it adequately wet. As the YHI needs charging after about 30 hours of continuous use, it was recharged. The instruments were left indoors at the end of each run, since the YHI was observed to give erratic readings after it was wetted by rain.

The thermocouples were automatically read at intervals of 30 seconds and a five minute average was computed and recorded. Visual observations were made on the WBGT measuring kits every 20 minutes so that the readings from the automated data collection system could be compared with the visual readings.

RESULTS AND DISCUSSION:

The ranges of environmental conditions that prevailed during the study were: ambient air temperature 18.7°C to 34.6°C, dew point 7°C to 24.9°C, radiation 0 to 1500 W/sq.m; and windspeed 0 to 7 m/s.

A paired t-test was done between the WBGT calculated from visual observations and the WBGT obtained from the automated data collection system. When a hypothetical difference of zero was assumed between the two sets of data (i.e. null hypothesis), significant differences were found in 16 out of 36 sets of readings; however, the mean differences were within 0.3°C, except for four values, which were accounted for by problems in the instrumentation on those particular days. This shows that the data collected by the automated data acquisition system was in good agreement with the visual measurements, which are the ones normally taken in practice.

The wet bulb globe temperature (WBGT) was calculated for each kit from the globe, dry bulb and wet bulb readings using the formula WBGT = 0.7 natural wet bulb + 0.2 globe + 0.1 dry bulb.

In the analysis and correlation of the extensive meteorological data collected by the automated data acquisition system, the days on which the experiment was carried out have been divided into the following four groups: 1) clear sky and sunny, 2) clear sky, sunny but hazy, 3) partly cloudy and 4) overcast weather.

A two way analysis of variance was carried out on the WBGT data for each day in the individual groups. Statistically significant differences were found between the different instruments in each of the four groupings. The differences are variable and it is difficult to draw generalized conclusions, such as which kit reads high or low compared to the Standard kit. Although differences observed were statistically significant, most of the differences were less than 0.5°C, a relatively minor difference with respect to application of such indices.

It was decided to evaluate the effect of radiation on the WBGT reading and the individual components (i.e. globe, dry bulb and wet bulb temperatures) when compared to the Standard kit values. The plots are presented in Figure 2. Each dot in the plot represents a data point. The WMK gives higher WBGT readings than the Standard at radiation ranging from 400 to 1050 W/sq.m, compared to YHI. The WMK black globe analog seems to agree with the Standard globe at low radiation ranging from 0 to 250 W/sq.m, but deviates substantially at higher radiation levels. The YHI globe seems to agree well with the Standard globe. The dry bulbs of both the WMK and YHI read higher than the Standard dry bulb, because of inadequate shading of the dry bulbs in these kits; compared to the WMK, the YHI dry bulb seems to read closer to the Standard dry bulb. The Weksler wet bulb reads high with radiation increasing from 350 to 950 W/sq.m, perhaps because of its configuration. The YHI wet bulb seems to agree well with the Standard wet bulb.

The effect of windspeed was also evaluated on these kits and the plots are shown in Figure 3. The WMK registers high WBGT values at windspeeds ranging from 1 to 3 m/s, above 3 m/s they seem to agree well with the Standard kit. The YHI WBGT deviates less from the standard WBGT. The WMK black globe analog reads lower than the Standard globe. The YHI globe agrees well with the Standard globe. The dry bulbs of the two kits register higher values than the Standard dry bulb at windspeeds ranging from 1 to 4 m/s and tend to agree above 5 m/s. The WMK wet bulb reads high at windspeeds ranging from 1 to 4 m/s; this phenomenon may be due to insufficient evaporative cooling that occurs at the wet bulb and also to the way the wick hangs from the bulb of the thermometer. The YHI wet bulb values seem to diverge little from the Standard wet bulb reading.

Overall comparisons were made between the globe, dry bulb and wet bulb thermometer reading of each instrument with the corresponding component in the Standard kit. The plots are presented in Figure 4. The WMK black globe analog reads lower than the Standard kit. The YHI globe seems to read close to the Standard globe. The WMK dry bulb reads higher than the Standard dry bulb. The YHI dry bulb reads higher than the Standard dry bulb, but the difference is not as pronounced as that of the WMK. The air temperature (ventilated) measured by the Cambridge instrument described above was compared with the Standard dry bulb; air temperature was lower than that measured by the Standard dry bulb. The WMK wet bulb readings are always higher in the low temperature range of 13-19^{o}C, but above this range they diverge less from the Standard wet bulb. The YHI wet bulb deviates less from the Standard compared to the WMK.

The inferences that can be drawn from the above plots give an indication of the significant differences found in the analysis of variance. It appears that the instruments do not follow a specific pattern. This is also evident in Figure 5, where the WBGT of each kit is plotted against time; the plot is made from data collected on one day of the study. Radiation and windspeed are also plotted to give an indication of their values. It seems that the response times of the instruments vary; the WKM is a fast-responding instrument, perhaps because of its black globe analog and the configuration of its thermometers.

The relation between the WMK WBGT and the STD. WBGT, and between the YHI WBGT and the STD. WBGT was studied by regression analysis using all the data collected during the study. The regression plots are presented in Figure 6 along with the regression equations and correlation coefficients. Even though the individual components of the WMK and YHI tend not to agree with those of the Standard kit, the final WBGT is in good agreement suggesting that the observed differences tend to balance themselves out in calculating the WBGT value for each device.

Regression analysis was done between the WGT (Botsball) and the Standard instrument WBGT. The regression plot is presented in Figure 7; the regression equation is WBGT = 1.044 WGT - 0.187 in ^{o}C ($r = 0.98$). It is interesting to note that the slope of the regression line derived for the Botsball in this study is identical to the slope of the regression equation obtained in another study[2]; only the intercepts are different. The regression equation derived in yet another study[6] is different from the one in this study; those studies were conducted in an indoor environment and the equation used for computing WBGT was different from the one in this study, which was conducted outdoors.

A time course of Botsball and windspeed are presented in Figure 8 to help evaluate how the windspeed influences the Botsball reading. It is not surprising to note that the response of the Botsball is to read high at low windspeeds and low at high windspeeds, in keeping with the evaporative cooling of the environment. The same type of response is also obtained from the natural wet bulb, the major contributor in calculating the WBGT as also depicted in Figure 8. This behavior of the Botsball is an important consideration when selecting a heat stress instrument.

CONCLUSIONS:

The relative sizes of the instruments used in this study are shown in Figure 1. The Botsball and the WMKs can be carried practically anywhere to measure heat stress. Thus, instead of measuring the WBGT at an established station and using that value as a representative of the place where the work is actually done, these two instruments can be carried right to the site of work to get an assessment of the heat stress at the work site. This is an important consideration for both the United States Army and industry at places where heat stress problems exist.

The WMK has a slide rule provided to calculate WBGT after reading the individual thermometers. The WMK produces a reading of WBGT, whereas with the Standard kit one needs to read the individual thermometers and then somehow compute the WBGT. However, the Botsball gives a simple, direct reading of the WGT which, by using the equation $WBGT = 1.044\ WGT - 0.187$ in ^{o}C can be converted to WBGT. Alternatively, the Botsball thermometer dial face can be colored as follows: green for less than 26.8°C, yellow from 26.8 to 28.4°C, pink from 28.4 to 30°C and red for greater than 30°C. These colors correspond to the heat stress risk zones associated with these WBGT values as specified in the Armed Forces Technical Bulletin, Medical, 175[10]; any other desired zones could be similarly color coded. This modification produces a simplification which strongly recommends use of this WGT instrument, in assessing heat stress; such a modified thermometer is shown in Fig. 1E.

The Botsball, the WMK and the YHI are all commercially available, whereas the Standard kit is not; the 15.2 cm globe needed to construct a Standard kit is not available commercially and can be obtained on contract from almost any metal spinning company, procurement of only a single globe could be quite expensive. If cost is not a factor, the YHI can be used as a suitable substitute for the Standard kit. The thermometers in the WMK are fragile and there is a tendency for the liquid columns to separate in the thermometers. In the case of Botsball the only fragile part is the glass on the dial of the thermometer, and the Botsball costs less than the other instruments used in this study. However, we are concerned that the black cloth bleaches with prolonged (30 days) use in sun, may become dirty and appears not possible to change.

On balance it appears that the Botsball is the simplest, most desirable, least expensive and most portable of the devices studied, provides an adequate value for assessing environmental heat stress, and should become more widely used than it is at present.

ACKNOWLEDGEMENT:

The authors thank Mr. J. R. Breckenridge for his valuable suggestions in writing this report and Ms. Ella H. Munro for the substantial statistical work.

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Figure 1 — Instruments used in the study.

Figure 2 — Difference of WBGT and its components of WMK and YHI from STD. WBGT as a function of radiation.

Figure 3 — Difference of WBGT and its components of WMK and YHI from STD. WBGT as a function of windspeed.

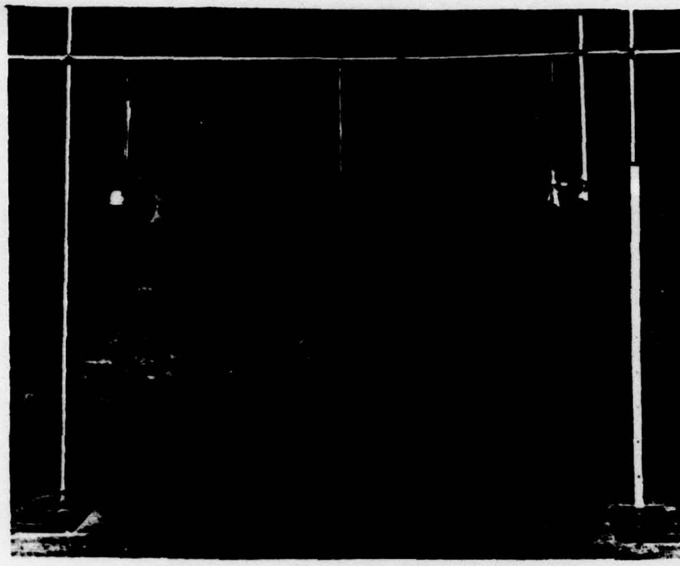
Figure 4 — Overall comparisons of globe, dry bulb and wet bulb temperatures.

Figure 5 — Time course of WBGT from the three instruments, windspeed and radiation.

Figure 6 — Regression plots illustrating the relation between WMK, WBGT and STD. WBGT and YHI, WBGT and STD. WBGT.

Figure 7 — Regression plots illustrating the relation betweeen Botsball and STD. WBGT.

Figure 8 — Time course of Botsball, natural wet bulb and windspeed.



STANDARD WBGT SET UP
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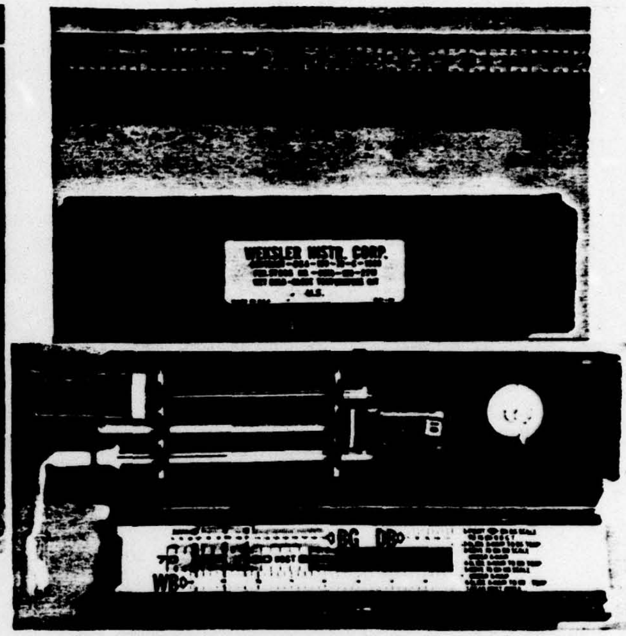

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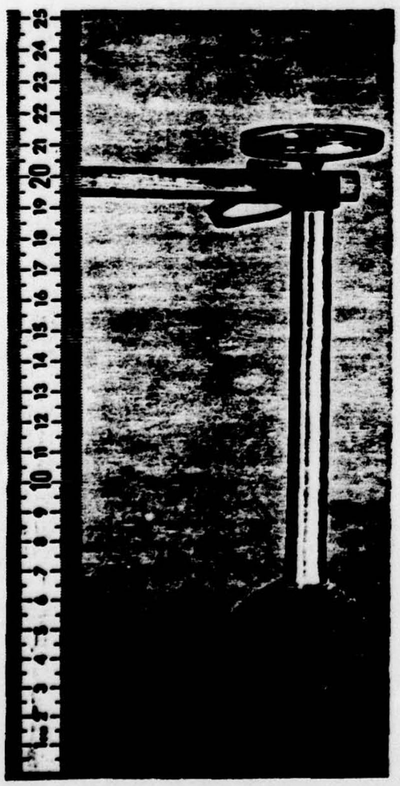

BOTSBALL THERMOMETER
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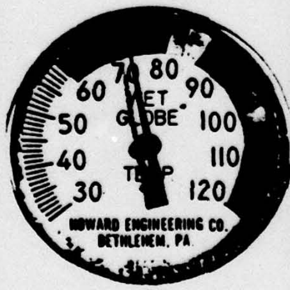

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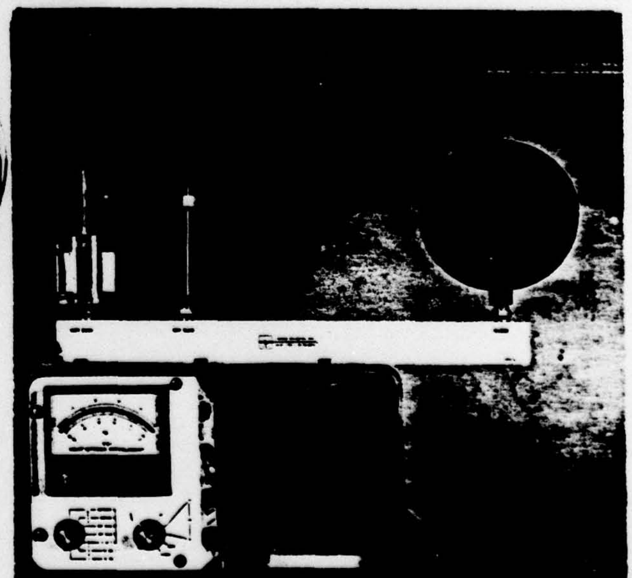

YELLOW SPRINGS HEAT STRESS INSTRUMENT
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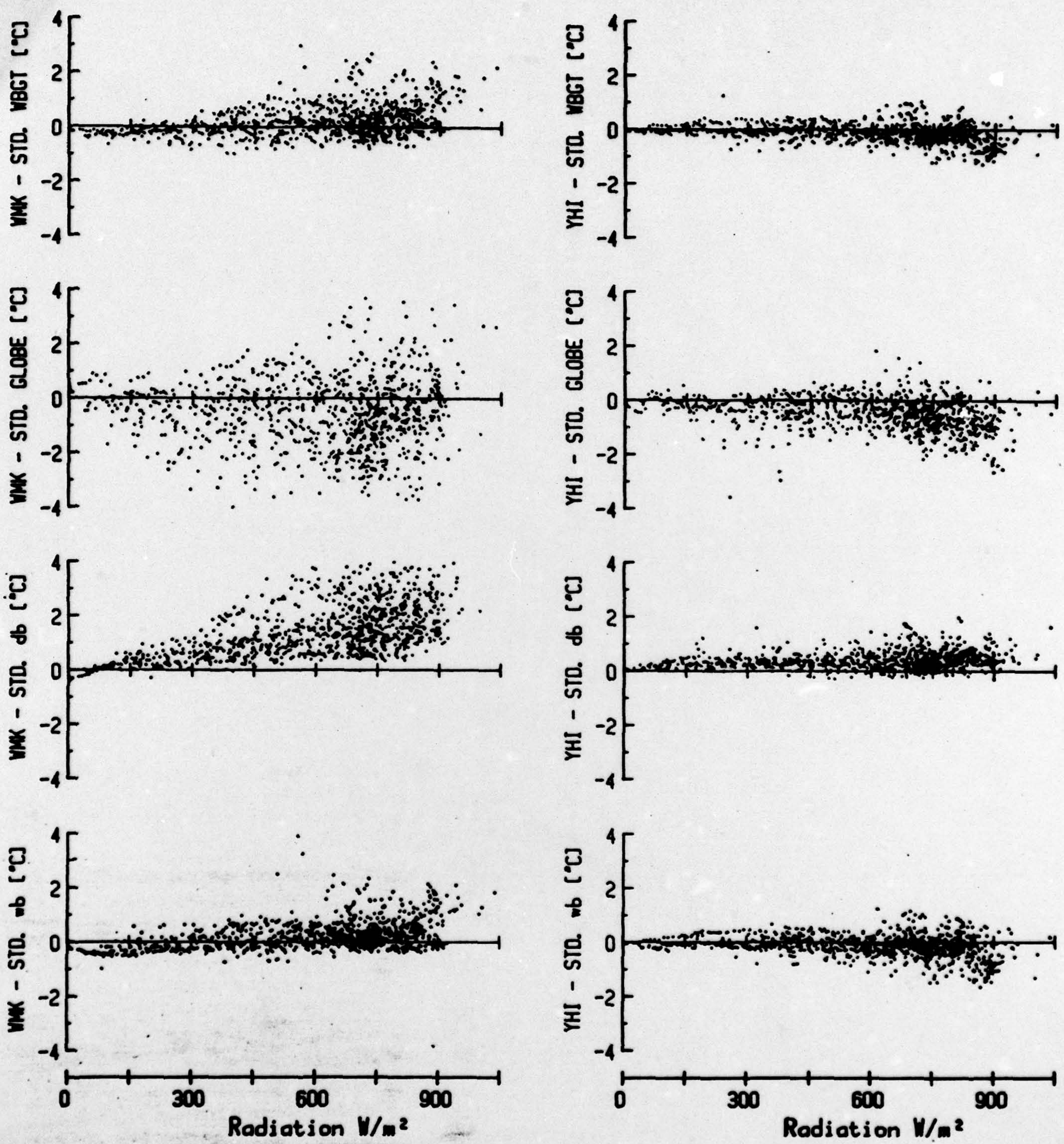
WMK - STD. WBGT [°C]
YHI - STD. WBGT [°C]
WMK - STD. GLOBE [°C]
YHI - STD. GLOBE [°C]
WMK - STD. db [°C]
YHI - STD. db [°C]
WMK - STD. wb [°C]
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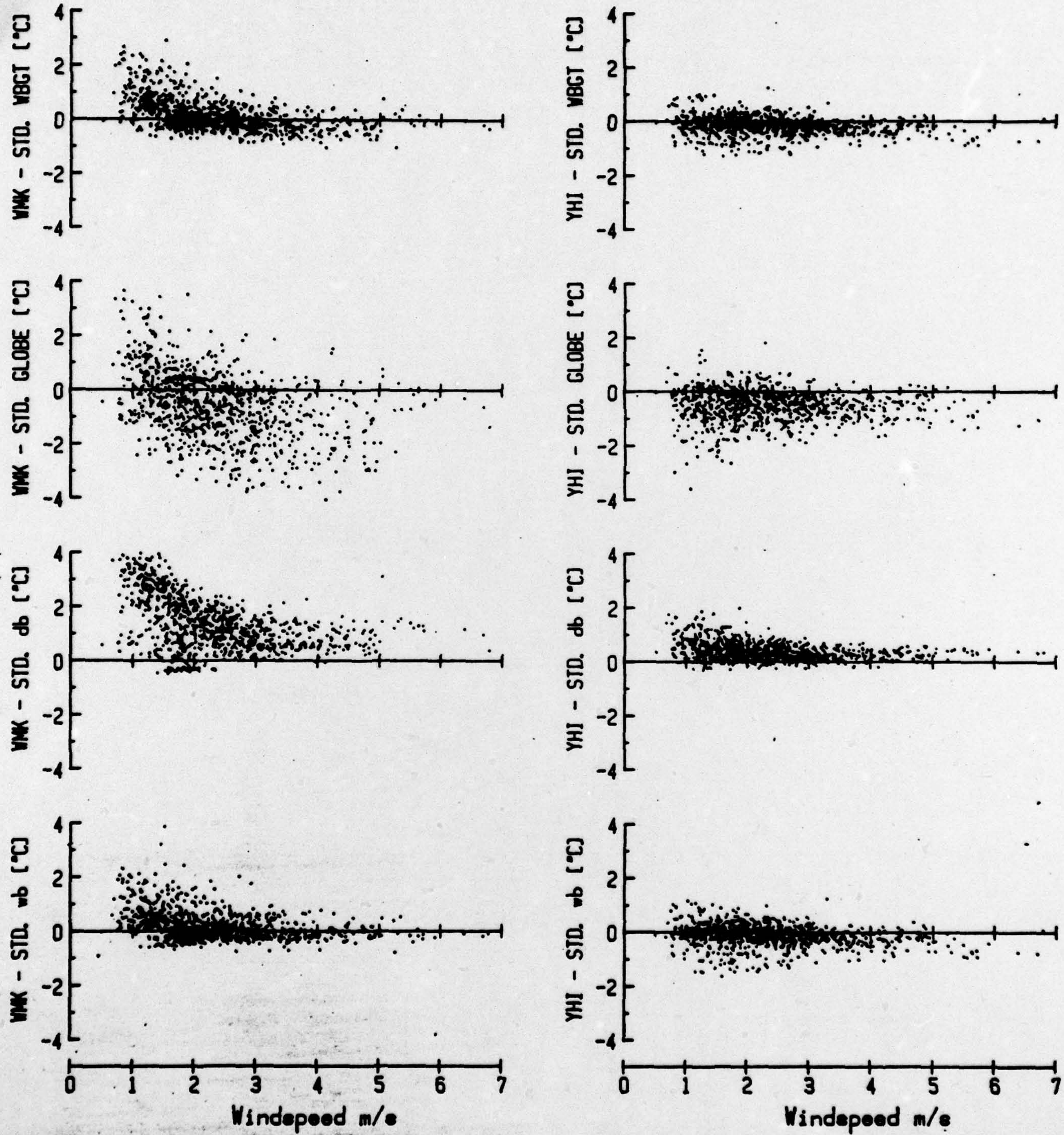
Radiation W/m²
Radiation W/m²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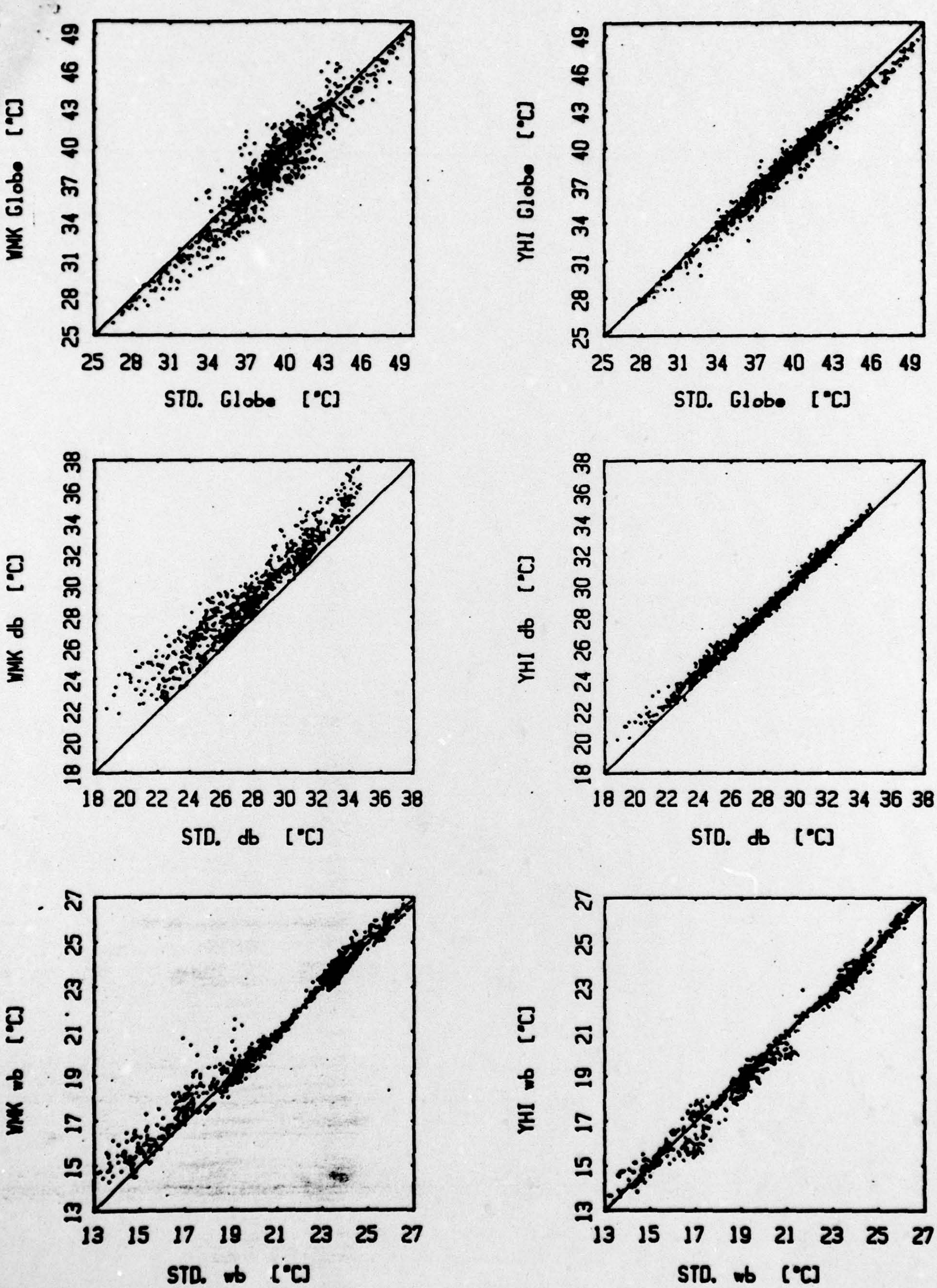
Windspeed m/s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STD. Globe [°C]
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STD. Globe [°C]
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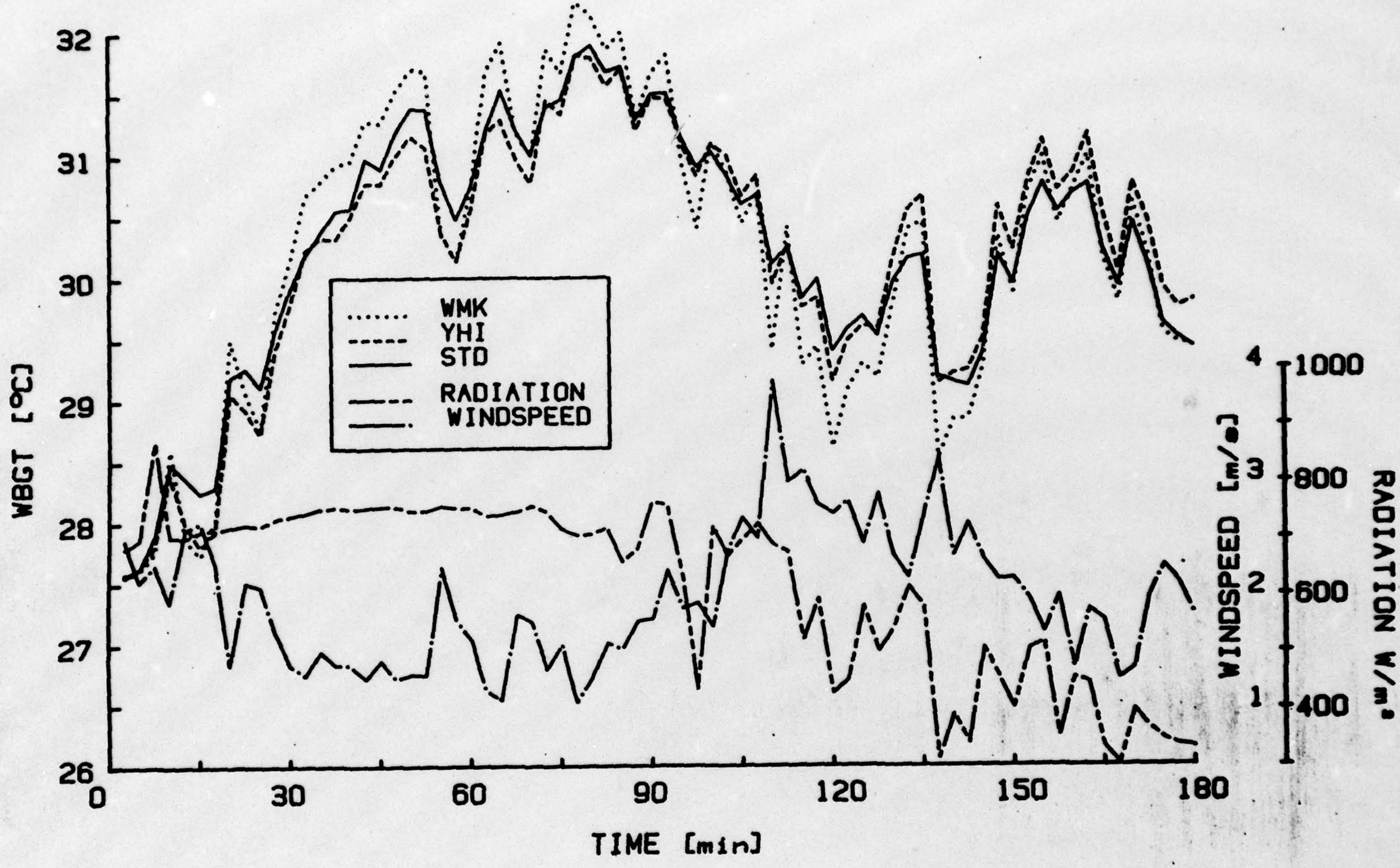
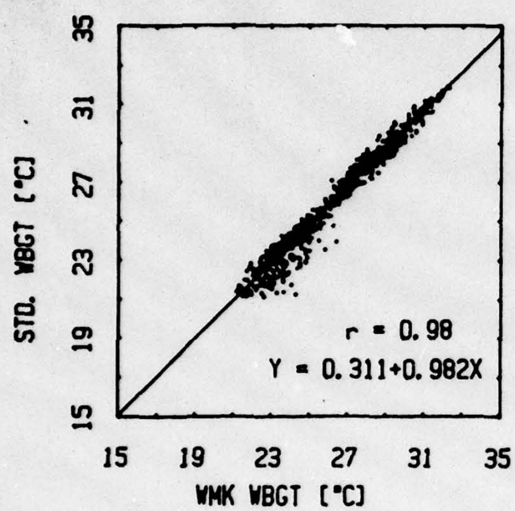
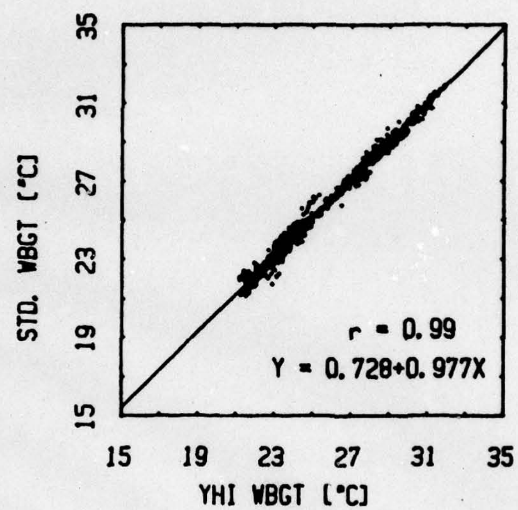
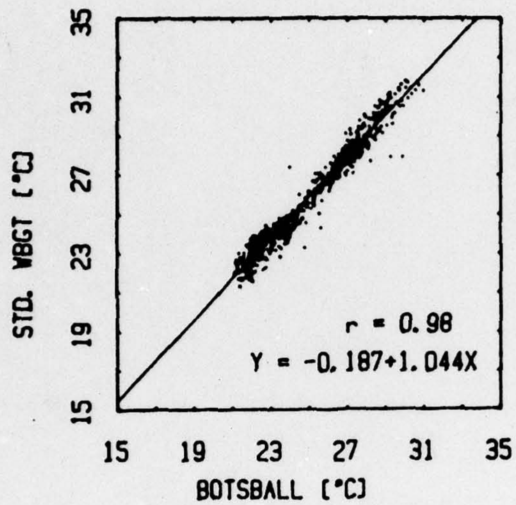
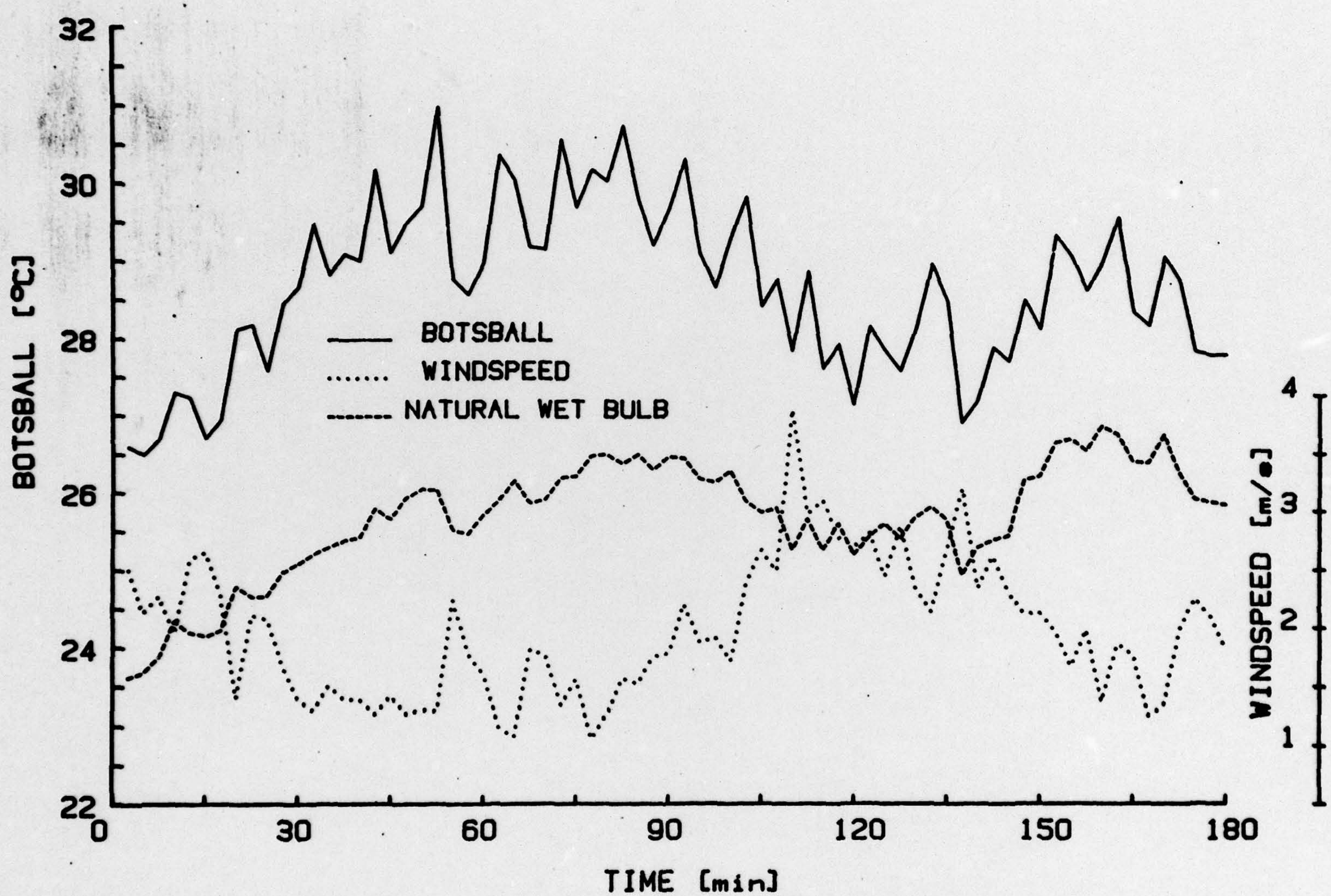


WBGT [°C]
32
31
30
29
28
27
26
0
30
60
90
120
150
180
TIME [min]
WMK
YHI
STD
RADIATION
WINDSPEED
WINDSPEED [m/s]
1
2
3
4
RADIATION W/m²
400
600
800
1000


STD. WBGT [°C]
15
19
23
27
31
35
r = 0.98
Y = 0.311+0.982X
WMK WBGT [°C]


STD. WBGT [°C]
15
19
23
27
31
35
r = 0.99
Y = 0.728+0.977X
YHI WBGT [°C]


r = 0.98
Y = -0.187+1.044X
STD. WBGT [°C]
BOTSBALL [°C]
15
19
23
27
31
35



BOTSBALL
WINDSPEED
NATURAL WET BULB
BOTSBALL [°C]
WINDSPEED [m/s]
TIME [min]